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The Mouth-Gut-Brain model: An interdisciplinary approach to facilitate reformulation of reduced fat products

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Abstract

The food industry faces the difficult challenge of reformulating many of their products to meet increasingly stringent targets to reduce energy density by adjusting fat and sugar levels. However, reducing fat in products raises multiple risks for consumer satisfaction because of the consequent effects on both the multimodal sensory experience of the product and the extent to which satiety post-ingestion meets expected satiety. Recognising that this complex problem requires an inter-disciplinary approach, the Mouth-Gut-Brain project brought together academic expertise in food and sensory science, the psychology of appetite and the biophysics of food microstructure, with the support of seven industry partners, to develop novel, innovative approaches to enable successful reformulation of fat in a snack context. The project recognised the multi-faceted nature of fat perception, and how it affects the psychological and physiological responses to consumption and ingestion. The outcomes of the research programme, comprising the characterisation of sensory and satiety responses of volunteers in the context of two novel fat-reduced snack products, will be published over the next year and will help inform future novel approaches to fat reduction.

Keywords:

Lipid, oleogustus, satiety, appetite, reformulation, compensation, perception

Reducing the energy content of foods, particularly through the reduction of total fat, saturated fat and sugars, continues to be a priority of both government and the food industry. In the UK, this is evidenced by the Childhood Obesity Plan (HM Government 2016) and the Calorie Reduction Programme launched in 2018 (Public Health England 2018). Virtually all European Union (EU) countries now have a policy position on reducing fat, sugars and salt in foods and drinks (Belc *et al.* 2018). These either encourage or require the food industry to reformulate products to meet targets for reductions in fat, sugars and salt. Reformulated products provide added choice to consumers wishing to control dietary intake; however, delivering consumer satisfaction that sustains long-term preference and purchase of reformulated products is a major challenge. An over-arching challenge for the food industry is, therefore, how to reformulate existing successful products to meet government targets without reducing consumer satisfaction and thereby risking rejection of reformulated versions. Evidence, including that from industry funded studies, indicates that in the longer term reformulation can lead to maladaptive consequences such as rebound hunger and overcompensation at subsequent meals (Chambers *et al.* 2015; Markey *et al.* 2016), and that some reformulated products on the market are less liked than standard products (Markey *et al.* 2015).

The food industry has risen to these challenges well, with salt reduction in the UK being an example of genuine success (Barry & Murphy 2017). But new thinking is needed to enable the food industry to meet new and more stringent rules on reformulation because it is more challenging, both technically and in relation to impacts on consumer satisfaction, to reduce fat and sugars in food. There is also increasing recognition that multi-disciplinary research teams are needed to meet this challenge, integrating scientific understanding of the chemical and physical properties of food, the biology of appetite and digestion and consumer psychology. To this end, the UK Research Councils, led by the Biotechnology and Biological Sciences Research Council (BBSRC), jointly hosted a special funding event, the Priming Food Partnerships Sandpit in 2016. The event brought together selected academics from multiple disciplines alongside partners from key industry stakeholders to develop novel projects relating to food structures, to try and meet the broader research needs of the food industry in relation to improving the health impact of foods through reformulation and processing.

One of the projects that emerged from the Priming Food Partnerships Sandpit, the Mouth-Gut-Brain (MGB) project, brought together a new partnership of academics with expertise in the psychology of appetite (University of Sussex), food and sensory science (University of Reading) and the biophysics of food microstructure (Quadram Institute), with the support of seven industry partners to develop novel, innovative approaches to enable successful food product reformulation. Initial funding was for an 18-month priming project (July 2017 – January 2019) to test the feasibility of these ideas in relation to fat reduction. This short paper explains the rationale and aims of the MGB project.

Consumer satisfaction and the risks of reformulation

The MGB project aimed to better characterise the risks of maladaption arising from reformulation and how they might be mitigated. At the core of the MGB project is the understanding that humans are, by nature, hypothesis testers (Klayman & Ha 1987), and make multiple predictions about products based on their knowledge and past experience (*e.g*. Cardello 2007; Deliza & MacFie 1996). Three ideas, drawing on broader concepts in behavioural economics (*e.g*. Thaler 2016; Hommes 2013) and research on expectations in consumer and sensory psychology (see Piqueras-Fiszman & Spence 2015), theoretically underpin the MGB approach to understanding consumer responses to reformulation. These are that:

1. consumers have expectations about products before consumption which are key drivers of product choice;
2. these expectations are tested when consumers consume the product, and the degree to which the product delivers the expected characteristics are the primary determinants of overall consumer satisfaction for that product; and
3. that the imprecise way expectations and experience are coded in the brain gives a window of opportunity for reformulation without negatively impacting consumer satisfaction.

A great deal of consumer research has focussed on the impact of the immediate sensory experience on product liking when a product is used. Studies with food products have consistently shown that expected liking is a strong and reliable predictor of product choice (see Lappalainen & Epstein 1990; Köster 2003; Köster 2009; Mela 2001; Mustonen *et al.* 2007). Product satisfaction then depends on the extent to which these consumer expectations about 'taste' (*i.e.* their sensory expectation) and the immediate sensory experience when a product is consumed are matched. But although sensory expectations clearly play a key role in consumer satisfaction, consumer's approach products with more than expectations about 'taste' alone; in particular, product purchase is also driven by expectations about the extent that a product will meet their current or future needs (often referred to as 'product utility'). Consumer satisfaction with a product is therefore better interpreted as the extent to which both sensory and utility expectations are met by the product, rather than simply being the product of sensory expectations and experience alone. Marketing and economics experts have long recognised that consumers judge products on multiple attributes including cost, convenience and lifestyle congruence. (Westbrook & Oliver 1991; Spreng *et al.* 1996; Nam *et al.* 2011). In the case of foods and drinks, it is possible to propose psychobiological approaches that model consumer satisfaction in terms of the impact of different ingredients, such as sugars and fat, on the experience of pleasure and altered appetite both during and after consumption. In the MGB project, specific memories about two key components of a product are suggested to be key contributors to this experience: the sensory characteristics of the product and the effect the product has on biologically relevant processes once consumed (its biological utility), generated by detection of nutrients during ingestion and digestion. In this context, expected satiety (*i.e.* the degree to which the product is expected to impact on consumer appetite) is emerging as a key measure of the biological utility of food and drink products (Forde *et al.* 2015; Brunstrom 2011).

Within this general theoretical framework, we hypothesised that reducing the fat content of a product would pose two particular risks in relation to consumer expectations:

1. that reducing the fat content of a familiar product would result in a discernible and undesirable difference between the consumer's expectations of the product's sensory characteristics and its actual sensory characteristics; and
2. that the reduced energy content of the product as a consequence of fat removal would result in a discernible and undesirable difference between the consumer's expectation of how satiating the food will be (*i.e*. biological utility) and their actual

physiologically response to ingestion of that food, increasing the risk of maladaptive behaviour (rebound hunger and later over-eating).

In relation to satiety expectations, a further complexity is that the consumer's sensory experience during food ingestion itself has been shown to modify expected satiety. For example, perceptions about the thickness and creaminess of a food have been shown to be particularly associated with expected satiety (McCrickerd *et al.* 2012; McCrickerd *et al.* 2015; Forde *et al.* 2013), and so the sensory changes arising from reduced fat reformulation could further impact the consumer's expectations of, as well as actual experience of, satiety. However, if an aim of product reformulation is to maintain the original sensory experience in a reformulated reduced-fat product, an additional risk then arises of a mismatch between the maintained higher satiety expectation based on its sensory characteristics and the weaker experience of actual satiety because of the reduced fat content (Chambers *et al.* 2015). Previous research has shown that products that generate strong satiety expectations but which then fail to deliver sufficient nutrients can lead to rebound hunger (*e.g.* Yeomans & Chambers 2011; Yeomans *et al.* 2014); consequently the intended benefit of reduced energy intake through fat reformulation may be lost because the consumer subsequently feels hungrier and so eats more later.

What then, theoretically, is the consequence of a mismatch between the expected and perceived experience of a product? Assimilation-contrast theory (Anderson 1973; Hovland *et al.* 1957; Cardello *et al.* 1985; Cardello & Sawyer 1992; Cardello 2007) suggests that the effects of expectations are critically dependent on the degree of similarity between the consumer's expected and actual experience of the product (Figure 1). To extrapolate these ideas to the hypothetical impact of fat reduction, if removing fat produces noticeable changes to the sensory characteristics of a product and those changes are out of line with consumer expectations, this discrepancy may lead to reduced consumer satisfaction and so reduced likelihood of a repeat purchase based on sensory effects alone. However, even if the change in the product's sensory profile was acceptable, its reduced fat content is likely to result in a weaker satiety response than expected and this may also lead to an undesired discrepancy (based on utility) in the consumer's experience that could also negatively impact satisfaction. Likewise, if a product is advertised as reduced fat, this knowledge is likely to generate an expectation that the product will be less filling (Tuorila *et al.* 1994). This low satiety expectation may be confirmed due to the actual reduced energy content of the reformulated product and, by assimilation with the satiety expectation, lead to an even weaker experience of actual satiety than would be expected from reformulation alone. All of these illustrations suggest fat reduction poses very significant risks for manufacturers in terms of consumer satisfaction; hence the MGB project aimed to test novel approaches to mitigate these risks.

The sensory complexity of fat

The reformulation for health agenda, and particularly the focus on reducing calories, considers sugar and fat reduction necessary to reduce the caloric content of widely liked and consumed products high in fat, salt and sugars. For sugar, the key sensory characteristic is easy to identify as sweet taste (see Mennella *et al.* 2016) and this can, at least in principle, be replaced by any one of a growing range of reduced or no-energy sweeteners (see Edwards *et al.* 2016), although even with sugar reduction there are additional challenges around the functional role of sugar on texture. Fat is even more complex since the orosensory experience of fat cannot be attributed to a single, simple sensory effect as is the case with sweet taste (Heinze *et al.* 2015; Liu *et al.* 2016; Zhou *et al.* 2016). Current thinking suggests that fat affects sensory experience in at least three different ways. The first, and probably oldest, idea is that fat imparts textural qualities to foods and drinks (Guinard & Mazzucchelli 1996; Schiffman *et al.* 1998), and sensory studies note that it is these somatosensory effects (mouthfeel attributes such as thick, creamy, mouthcoating, greasy) that are often most noticed by consumers (Heinze *et al.* 2015; Drewnowski 1992; Oppermann *et al.* 2017). Fat contributes to key physical parameters such as viscosity (*e.g.* Bayarri *et al.* 2006; Mela *et al.* 1994) and tribological properties (the impact on oral lubrication: Prakash *et al.* 2013). The finding that the neural response to fat can be partly mimicked by non-fat solutions varying in viscosity adds weight to the idea that fat perception is, at least partly, driven by stimulation of somatosensory receptors in the mouth (Stice *et al.* 2013; De Araujo & Rolls 2004). Fats also deliver volatile flavour compounds either as a carrier of lipophilic aroma compounds or as a direct contributor of lipid-derived flavour compounds, which are then perceived through both orthonasal and retronasal pathways (*i.e*. before food enters the mouth, or during ingestion) by consumers (Drewnowski & Almiron-Roig 2009). Most recently, the finding that humans can detect certain free fatty acids in the mouth has led to the suggestion that free fatty acid detection is the sixth primary taste ('oleogustus': Keast & Costanzo 2015; Running *et al.* 2015). To add even more complexity, fat perception also depends on individual differences in genetic make-up and the personal history of fat consumption (Heinze *et al.* 2015; Zhou *et al.* 2016; Stewart *et al.* 2010; Tucker *et al.* 2017). While this short report can only touch on the true complexity of fat perception and its contribution to the overall sensory experience of products containing fat, the key point is that any attempt to reduce the fat content of products will need to mitigate multiple sensory consequences, all of which pose risks to consumer acceptance of fat reduction. For this reason, the studies conducted in the initial MGB project have taken care to characterise individual differences in sensory response to the prototypical reduced fat products generated within the project (described later).

Food restructuring as a means of achieving fat reduction: Historical and recent approaches

Fat replacers, ingredients that in some way 'mimic' the textural and sensory attributes that fat contributes to a product, historically were used in attempts to replace fat in products (see Lucca & Tepper 1994 for an early review of that approach). These compounds typically target the somatosensory aspects of fat perception (*e.g*. by adding viscosity to emulsions) and encompass a wide range of products based on modified carbohydrates, proteins and certain fibres. But as noted earlier, fat perception involves more than textural effects alone, and so the fat-replacer approach can only ever partly replace the sensory effects derived from fat. For example, any reduction in orally available free fatty acids would reduce oleogustus. An alternative approach is to restructure the existing fat content. Key to this idea is the realisation that only a small proportion of the fat ingested into the mouth is ever in contact with the sensory receptors that underpin fat perception. One approach has been to use multiple emulsion systems (Perez-Moral *et al.* 2014), whereby the core region of individual emulsified oil droplets contains added water, so that the surface region of the droplets, where the interaction with sensory receptors is made, is entirely composed of fat. This maintains the consumer's oral experience of fat but allows the total fat content of a product to be reduced.

The MGB approach: Evidence-based testing of consumer tolerance to fat reduction

The MGB project set out to test key aspects of the complex interplay between signals arising from the mouth and gut, and how these are represented in the brain. The key inter-relationships are shown in Figure 2. Within the constraints of an initial 18-month funded project, we set out to define the gap between sensory expectation and subsequent satiety response (mouth-gut discordance). As noted above, traditional approaches to low-fat reformulation have concentrated on mouthfeel, yet the oleogustus response to fat results from the perception of fatty acids. We propose that by modifying fat delivery, and the level and profile of free fatty acids in reformulated products, we can reduce the gap between the consumer's sensory expectation and gut/brain feedback signaling, leading to more acceptable and satiating reduced fat products. Accordingly, we set out to answer the following questions about how consumers might tolerate fat reduction.

1. Can the fat content of a product be reduced without affecting consumers' expectations of satiety?

We have developed a novel, multiple emulsion-based product (essentially replacing the core of oil droplets with water) during the initial phases of the project. A range of reduced fat versions (up to 60% fat reduction) of this product were developed, which were matched for mouthfeel. We then defined sensory tolerance as the maximum amount that fat could be lowered without affecting consumers' expectations of satiety.

2. To what extent can the difference between expected and actual satiety be tolerated by consumers?

Having established a reliable test product and characterised how consumers' expected satiety varies as a function of the fat content, we subsequently tested consumers' actual experience of satiety following consumption of the product using a standard preload design (Yeomans 2018). This method was used to examine what degree of fat reduction is tolerated before the discrepancy between expected and actual satiety leads to rebound hunger.

3. Can rebound hunger be countered using targeted gut-based fat signals?

Here, a more complex snack food was developed with the help of industrial partners. Different versions were produced with varying fat and free fatty acid contents. Using these products in a second preload study, we tested the extent to which inclusion of enhanced oleogustus signalling (through the testing of the fatty acid sensitivity of the subjects and subsequent addition of appropriate levels of fatty acids to the formulation) could be used to mitigate the reduced satiety associated with actual fat reduction.

Testing these three initial hypotheses, the outcomes of the MGB project, which will be published over the next 12 months, provides proof-in-principle of the idea that carefully targeted fat reduction can be achieved without impacting consumer satisfaction if products are designed to align the sensory (Mouth) and gut-based (Gut) processing of fat. The outcomes will be published in a series of journal articles, with the first papers appearing later in 2019.

Industrial and consumer relevance

It is unusual for a research project to have been developed as a collaboration between an inter-disciplinary academic team and multiple industrial partners. The engagement of the industry partners in this project has added hugely to the project's scope and industrial relevance. That industry is willing to commit research effort in this way is evidence of the urgent need for integrated solutions to product reformulation. We look forward to reporting the outcomes of the work so far in the coming months. The outcomes of the MGB project will provide invaluable lessons for food manufacturers worldwide on novel, integrated approaches to fat reduction, in addition to new methodologies to help better characterise how individual consumers respond to these changes.

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Figure 1: **Schematic summary of assimilation-contrast of expectations (adapted from ideas in Piqueras-Fiszman & Spence 2015).** Where there is no perceived difference between expectations about and experience of a product (the Neutral zone), expectations are strengthened but the experience is unaltered. Where there are small discrepancies between expectations and experience, the expectations are assimilated and the experience

is either enhanced (Positive Assimilation) or reduced (Negative Assimilation). Where the discrepancy is large, the contrast between expectations and experience is too great and the experience is negative. In everyday life and indeed in most research studies, assimilation is more commonly observed because it is rare for sources of product information such as labels to be misleading (incongruent) to such an extent as to result in a contrast effect (such as in Yeomans *et al.* 2008).

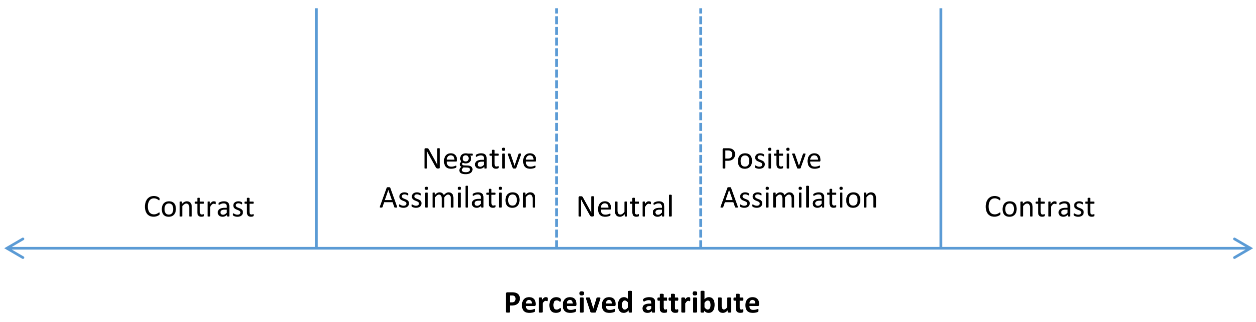

Figure 2: Schematic of the Mouth-Gut-Brain Model.

A (Mouth-Brain, hedonic): tasting food leads to hedonic response in the brain in addition to an expectation of satiety, B (Mouth-Brain, expected satiety). C (Mouth-Gut): nutrients are absorbed after food is consumed, with taste receptors located throughout the gastrointestinal tract acting as metabolite receptors. D (Gut-Brain): satiety hormones are released following food intake, signaling post-ingestive satiety in the brain. E (Brain-post-ingestive-Brain expectation and hedonic signals): post-ingestive satiety signals may match or mismatch sensory expected satiety (B) and influence the consumer's expectations about how much they will enjoy eating it in the future and the likelihood that they will consume it again (F).